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DESCRIPTION

HIGH-STRENGTH STEEL SHEETS EXCELLENT IN HOLE-EXPANDABILITY AND DUCTILITY

[Technical Field]

The present invention relates to high-strength steel sheets having thicknesses of not more than approximately 6.0 mm and tensile strengths of not less than 590 N/mm^2, or, in particular, not less than 980 N/mm^2. The steel sheets are excellent in hole-expandability and ductility and are used primarily as automotive steel sheets subject to press-forming.

[Background Art]

In recent years, efforts have been made to develop hot-rolled high-strength steel sheets excellent in press formability in order to meet the increasing needs for car weight reductions as means to improve automotive fuel efficiency as well as for integral forming as a means to cut down production costs. Dual-phase steel sheets comprising ferritic and martensitic structures have, conventionally, been known as hot-rolled steel sheets for forming.

Being made up of a composite structure comprising a soft ferrite phase and a hard martensite phase, dual-phase steel sheets are inferior in hole-expandability because voids develop from the interface between the two phases of significantly different hardnesses and, therefore, they are unfit for uses that demand high hole-expandability, such as suspension members.

In comparison, Japanese Unexamined Patent Publications No. 4-88125 and No. 3-180426 propose methods for manufacturing hot-rolled steel sheets primarily comprising bainite and, thus, having excellent hole-expandability. However, the steel sheets manufactured by the proposed methods are limited in applicability because of inferior ductility.

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Japanese Unexamined Patent Publications No. 6-293910, No. 2002-180188, No. 2002-180189 and No. 2002-180190 propose steel sheets comprising mixed structures of ferrite and bainite and having compatible hole-expandability and ductility. However, needs for greater car weight reduction and more complicated parts and members demand still greater hole-expandability, higher workability and greater strength than can be provided by the proposed technologies.

The inventors discovered that the condition of cracks in punched holes is important for the improvement of hole-expandability without an accompanying deterioration of ductility, as disclosed in Japanese Unexamined Patent Publications No. 2001-342543 and No. 2002-20838. That is to say, the inventors discovered that particle size refinement of (Ti, Nb)N produces fine uniform voids in the cross section of punched holes, relieves stress concentration during the time when the hole is expanded and thereby improves hole-expandability.

The discoveries included the use of Mg-oxides as a means for accomplishing the particle size refinement of (Ti, Nb)N. However, the proposed technology, which controls only oxides, does not provide adequate effect because the degree of freedom in the control of oxygen is low, the total volume of oxygen available is small because free oxygen after deoxidation is used, and, therefore, the desired degree of dispersion has been difficult to obtain.

[Summary of the Invention]

The object of the present invention is to solve the conventional problems described above and, more specifically, to provide high-strength steel sheets having tensile strength of not less than 590 N/mm^2, and preferably not less than 980 N/mm^2, and excellent in both hole-expandability and ductility.

The inventors conducted various experiments and studies on particle size refinement of (Ti, Nb)N in order

to relieve stress concentration during hole-expansion work and thereby improve hole-expandability by forming fine uniform voids in the cross sections of the punched holes.

Although it has conventionally been said that sulfides cause deterioration of hole-expandability, the experiments and studies led to a discovery that Mg-sulfides are conducive to the improvement of hole-expandability by the particle size refinement of TiN because Mg-sulfides precipitating at high temperatures act as the nucleus for forming (Ti, Nb)N precipitates and Mg-sulfides precipitating at low temperatures inhibit the growth of (Ti, Nb)N by way of competitive precipitation with (Ti, Nb)N.

It was also discovered that, in order to avoid the precipitation of manganese sulfides and achieve the above-described actions by the precipitation of Mg-sulfides, it is necessary to keep the amounts of addition of oxygen, magnesium, manganese and sulfur within certain limits which; in turn, facilitates the attainment of more uniform and finer particles (Ti, Nb)N than those obtained by the use of Mg-oxides alone. The following invention was made based on the findings described above.

(1) High-strength steel sheet excellent in hole-expandability and ductility, characterized by;

comprising, in mass%,

C: not less than 0.01 % and not more than 0.20 %

Si: not more than 1.5 %,

Al: not more than 1.5 %,

Mg: not less than 0.5 % and not more than 3.5 %,

P: not more than 0.2 %,

S: not less than 0.0005 % and not more than 0.009 %,

N: not more than 0.009 %,

Mg: not less than 0.0006 % and not more than 0.01 %,

O: not more than 0.005 % and

Ti: not less than 0.01 % and not more than 0.20 % and/or Nb: not less than 0.01 % and not more than 0.10 %,

with the balance consisting of iron and unavoidable impurities,

having Mn%, Mg%, S% and O% satisfying equations (1) to (3), and

having the structure primarily comprising one or more of ferrite, bainite and martensite.

$[Mg\%] \geq ([O\%]/16 \times 0.8) \times 24$ ... (1)

$[S\%] \leq ([Mg\%]/24 - [O\%]/16 \times 0.8 + 0.00012) \times 32$ ... (2)

$[S\%] \leq 0.0075/[Mn\%]$ ... (3)

(2) High-strength steel sheet excellent in hole-expandability and ductility described in item (1), characterized by containing not less than 5.0×10^2 per square millimeter and not more than 1.0×10^7 per square millimeter of composite precipitates of MgO, MgS and (Nb, Ti)N of not smaller than 0.05 μm and not larger than 3.0μm.

(3) High-strength steel sheet excellent in hole-expandability and ductility described in item (1), characterized by having Al% and Si% satisfying equation (4).

$[Si\%] + 2.2 \times [Al\%] \geq 0.35$ ... (4)

(4) High-strength steel sheet excellent in hole-expandability and ductility described in item (2), characterized by having Al% and Si% satisfying equation (4).

$[Si\%] + 2.2 \times [Al\%] \geq 0.35$ (4)

(5) High-strength steel sheet excellent in hole-expandability and ductility described in any of items (1) to (4), characterized by;

having Ti%, C%, Mn% and Nb% satisfying equations (5) to (7),

having the structure primarily comprising bainite, and

having a strength exceeding 980 N/mm^2.

$0.9 \leq 48/12 \times [C\%]/[Ti\%] < 1.7$ ... (5)

$$50227\times[C\%]-4479\times[Mn\%]>-9860 \quad \ldots (6)$$

$$811\times[C\%]+135\times[Mn\%]+602\times[Ti\%]+794\times[Nb\%]>465 \quad \ldots (7)$$

(6) High-strength steel sheet excellent in hole-expandability and ductility described in any of items (1) to (4), characterized by;

having C%, Si%, Al% and Mn% satisfying equation (8),

having the structure primarily comprising ferrite and martensite, and

having a strength exceeding 590 N/mm^2.

$$-100\leq-300[C\%]+105[Si\%]-95[Mn\%]+233[Al\%] \quad \ldots (8)$$

(7) High-strength steel sheet excellent in hole-expandability and ductility described in item (6), characterized in that;

not less than 80 % of crystal grains having a short diameter (ds) to long diameter (dl) ratio (ds/dl) of not less than 0.1 exist in the steel structure.

(8) High-strength steel sheet excellent in hole-expandability and ductility described in item (7), characterized in that;

not less than 80 % of ferrite crystal grains having a diameter of not less than 2 μm exist in the steel structure.

(9) High-strength steel sheet excellent in hole-expandability and ductility described in any of items (1) to (4), characterized by;

having C%, Si%, Mn% and Al%, satisfying equation (8),

having the structure primarily comprising ferrite and bainite, and

having the strength exceeding 590 N/mm^2.

$$-100\leq-300[C\%]+105[Si\%]-95[Mn\%]+233[Al\%] \quad \ldots (8)$$

(10) High-strength steel sheet excellent in hole-expandability and ductility described in item (9), characterized in that;

not less than 80 % of crystal grains having a short diameter (ds) to long diameter (dl) ratio (ds/dl) of not

less than 0.1 exist in the steel structure.

(11) High-strength steel sheet excellent in hole-expandability and ductility described in item (10), characterized in that;

not less than 80 % of ferrite crystal grains having a diameter of not less than 2 μm exist in the steel structure.

(12) A method for manufacturing high-strength steel sheet excellent in hole-expandability and ductility, which has the structure primarily comprising ferrite and martensite and a strength in excess of 590 N/mm^2, characterized by the steps of;

completing the rolling of steel having a composition described in any of items (1) to (4) at a finish-rolling temperature of not lower than the Ar_3 transformation point,

cooling at a rate of not less than 20 °C/sec, and

coiling at a temperature below 300 °C.

(13) A method for manufacturing high-strength steel sheet, excellent in hole-expandability and ductility, which has the structure primarily comprising ferrite and martensite and a strength in excess of 590 N/mm^2 characterized by the steps of;

completing the rolling of steel having a composition described in any of items (1) to (4) at a finish-rolling temperature of not lower than the Ar_3 transformation point,

cooling to between 650 °C and 750 °C at a rate of not less than 20 °C/sec,

air-cooling at said temperature for not longer than 15 seconds,

re-cooling, and

coiling at a temperature below 300 °C.

(14) A method for manufacturing high-strength steel sheet, excellent in hole-expandability and ductility, which has the structure primarily comprising ferrite and

bainite and a strength in excess of 590 N/mm^2; characterized by the steps of;

completing the rolling of steel having a composition described in any of items (1) to (4) at a finish-rolling temperature of not lower than the Ar_3 transformation point,

cooling at a rate of not less than 20 °C/sec, and

coiling at a temperature of not lower than 300 °C and not higher than 600 °C.

(15) A method for manufacturing high-strength steel sheet excellent in hole-expandability and ductility, which has the structure primarily comprising ferrite and bainite and a strength in excess of 590 N/mm^2; characterized by the steps of;

completing the rolling of steel having a composition described in any of items (1) to (4) at a finish-rolling temperature of not lower than the Ar_3 transformation point,

cooling to between 650 °C and 750 °C at a rate of not less than 20 °C/sec,

air-cooling at said temperature for not longer than 15 seconds,

re-cooling, and

coiling at a temperature of not lower than 300 °C and not higher than 600 °C.

[Brief Description of the Drawings]

Figure 1 shows the relationship between tensile strength and ductility.

Figure 2 shows the relationship between tensile strength and hole-expanding ratio.

Figure 3 shows the relationship between tensile strength and ductility.

Figure 4 shows the relationship between tensile strength and hole-expanding ratio.

Figure 5 shows the relationship between ductility and short-diameter to long-diameter ratio (ds/dl).

Figure 6 shows the relationship between ductility and the percentage of ferrite grains not smaller than 2 μm.

Figure 7 shows the relationship between tensile strength and ductility.

Figure 8 shows the relationship between tensile strength and hole-expanding ratio.

Figure 9 shows the relationship between ductility and short-diameter to long-diameter ratio (ds/dl).

Figure 10 shows the relationship between ductility and the percentage of ferrite grains not smaller than 2 μm.

[The Most Preferred Embodiment]

With attention focused on the end-face properties of punched holes, the present invention improves hole-expandability by adjusting the amount of addition of O, Mg, Mn and S so that Mg-oxides and sulfides are uniformly and finely precipitated, generation of large cracks during pouching is inhibited and end-face properties of punched holes are made uniform.

Constituent features of the present invention are described below in detail.

First, the reason why the composition of the high-strength steel sheets according to the present invention should be limited will be described. In addition % means mass%.

C is an element that affects the workability of steel. Workability deteriorates as C content increases. The C content should be not more than 0.20 % because carbides deleterious to hole-expandability (such as pearlite and cementite) are formed when the C content exceeds 0.20 %. It is preferable that the C content is not more than 0.1 % when particularly high hole-expandability is demanded. Meanwhile, the C content should be not less than 0.01 % for the securing of necessary strength.

Si is an element that effectively enhances ductility

by inhibiting the formation of deleterious carbides and increasing ferrite content. Si also secures strength of steel by solid-solution strengthening. It is therefore desirable to add Si. Even so, the Si content should be not more than 1.5 % because excessive Si addition not only lowers chemical convertibility but also deteriorates spot weldability.

Al too, like Si, is an element that effectively enhances ductility by inhibiting the formation of deleterious carbides and increasing ferrite content. Al is particularly necessary for providing compatibility between ductility and chemical convertibility.

Al has conventionally been considered necessary for deoxidation and added in amounts between approximately 0.01 % and 0.07 %. Through various studies, the inventors discovered that abundant addition of Al improves chemical compatibility without deteriorating ductility even in low -Si steels.

However, the Al content should be not more than 1.5 % because excessive addition not only saturates the ductility enhancing effect but also lowers chemical compatibility and deteriorates spot weldability. In particular, it is preferable to keep the Al content not more than 1.0 % when chemical treatment conditions are severe.

Mn is an element necessary for the securing of strength. At least 0.50 % of Mn must be added. In order to secure quenchability and stable strength, it is preferable to add more than 2.0 % of Mn. As, however, excessive addition tends to cause micro- and macro-segregations that deteriorate hole-expandability, the Mn addition should not be more than 3.5 %.

P is an element that increases the strength of steel and enhances corrosion resistance when added with Cu. However, the P content should be not more than 0.2 % because excessive addition deteriorates weldability, workability and toughness. Therefore, the P content is

not more than 0.2 %. Particularly when corrosion resistance is not important, it is preferable to keep the P content not more than 0.03 % by attaching importance to workability.

S is one of the most important additive elements used in the present invention. S dramatically enhances hole-expandability by forming sulfides, which, in turn, form nucleus of (Ti, Nb)N, by combining with Mg and contributing to the particle size refinement of (Ti, Nb)N by inhibiting the growth thereof.

In order to obtain this effect, it is necessary to add not less than 0.0005 % of S, and it is preferable to add not less than 0.001 % of S. However, the upper limit of S addition is set at 0.009 % because excessive addition forms Mg-sulfides and, thereby, deteriorates hole-expandability.

In order to secure workability, N content should preferably be as low as possible as N contributes to the formation of (Ti, Nb)N. The N content should be not more than 0.009 % as coarse TiN is formed and workability deteriorates thereabove.

Mg is one of the most important additive elements used in the present invention. Mg forms oxides by combining with oxygen and sulfides by combining with S. The Mg-oxides and Mg-sulfides thus formed provide smaller precipitates and more uniform dispersion than in conventional steels prepared with no Mg addition.

The finely dispersed precipitates in steel effectively enhance hole-expandability by contributing to fine dispersion of (Ti, Nb)N.

Mg must be added not less than 0.0006 % as sufficient effect is unattainable therebelow. In order to obtain sufficient effect, it is preferable to add not less than 0.0015 % of Mg.

Meanwhile, the upper limit of Mg addition is set at 0.01 % as addition in excess of 0.01 % not only causes saturation of the improving effect but also deteriorates

hole-expandability and ductility by deteriorating the degree of steel cleanliness.

O is one of the most important additive elements used in the present invention. O contributes to the enhancement of hole-expandability by forming oxides by combining with Mg. However, the upper limit of O content is set at 0.005 % because excessive addition deteriorates the degree of steel cleanliness and thereby causes the deterioration of ductility.

Ti and Nb are among the most important additive elements used in the present invention. Ti and Nb effectively form carbides, increase the strength of steel, contribute to the homogenization of hardness and, thereby, improve hole-expandability. Ti and Nb form fine and uniform nitrides around the nucleus of Mg-oxides and Mg-sulfides. It is considered that the nitrides thus formed inhibit the generation of coarse cracks and, as a result, dramatically enhance hole-expandability by forming fine voids and inhibiting stress concentration.

In order to effectively achieve these effects, it is necessary to add at least not less than 0.01 % of each Nb and Ti.

Additions of Ti and Nb should respectively be not more than 0.20 % and 0.10 % because excessive addition causes deterioration of ductility by precipitation strengthening. Ti and Nb produce the desired effects when added either singly or in combination.

Furthermore, one or more of the following elements may also be added to the steel sheets according to the present invention.

Ca, Zr and REMs (rare-earth-metals) control the shape of sulfide inclusions and, thereby, effective enhance hole-expandability. In order to obtain this effect, not less than 0.0005 % of one or more of Ca, Zr and REMs should be added. Meanwhile, the upper limit of addition is set at 0.01 % because excessive addition lowers the degree of steel cleanliness and, thereby,

impairs hole-expandability and ductility.

Cu enhances corrosion resistance when added together with P. In order to obtain this effect, it is preferable to add not less than 0.04 % of Cu. However, the upper limit of addition is set at 0.4 % because excessive addition increases quench hardenability and impairs ductility.

Ni is an element that inhibits hot cracking resulting from the addition of Cu. In order to obtain this effect, it is preferable to add not less than 0.02 % of Ni. However, the upper limit of addition is set at 0.3 % because excessive addition increases quench hardenability and impairs ductility, as in the case of Cu.

Mo effectively improves hole-expandability by inhibiting the formation of cementite. Addition of not less than 0.02 % of Mo is necessary for obtaining this effect. However, the upper limit of addition is set at 0.5 % because Mo too enhances quench hardenability and, therefore, excessive addition thereof lowers ductility.

V is an element that contributes to the securing of strength by forming carbides. In order to obtain this effect, not less than 0.02 % of V must be added. However, the upper limit of addition is set at 0.1 % because excessive addition lowers ductility and proves costly.

Cr, like V, is an element that contributes to the securing of strength by forming carbides. In order to obtain this effect, not less than 0.02 % of Cr must be added. However, the upper limit of addition is set at 1.0 % because Cr too enhances quench hardenability and, therefore, excessive addition thereof lowers ductility.

B is an element that effectively reduces fabrication cracking that is a problem with ultra-high tensile steels. In order to obtain this effect, not less than 0.0003 % of B must be added. However, the upper limit of addition is set at 0.001 % because B too enhances quench

hardenability and, therefore, excessive addition thereof lowers ductility.

Through various studies intended for finding solutions for the problems described above, the inventors discovered that it is possible to finely disperse (Nb, Ti)N by using the Mg-oxides and Mg-sulfides that are obtainable by adjusting the amounts of addition of O, Mg, Mn and S under certain conditions.

That is to say, it becomes possible to use the action as the nucleus and the action to inhibit growth described earlier by allowing adequate precipitation of Mg-oxides and allowing precipitation of Mg-sulfides by controlling the precipitation temperature thereof while impeding the precipitation of Mg-sulfides. In order to make this goal possible, the following three equations were derived.

As the present invention uses Mg-sulfides in addition to Mg-oxides, the amount of addition of Mg must be greater than that of O. While O forms oxides with Al and other elements, the inventors discovered that the effective-O that combines with Mg is 80 % of the assayed amount. Thus, the amount of Mg addition to form a large enough quantity of sulfides to realize the improvement of hole-expandability should be greater than 80 % of the assayed amount. Therefore, the amount of Mg addition must satisfy equation (1).

S, which is essential in forming Mg-sulfides, forms Mn-sulfides when present in large quantities. When precipitating in small quantities, Mn-sulfides are present mixed with Mg-sulfides and have no effect to deteriorate hole-expandability. When precipitating in large quantities, however, Mn-sulfides precipitate singly or affect the properties of Mg-sulfides, and thereby deteriorate hole-expandability, though details are unknown. Therefore, the quantity of S must satisfy equation (2) in respect of Mn and the effective amount of O.

When both of Mn and S are present in large quantities, Mn-sulfides precipitate at high temperatures, inhibit the production of Mg-sulfides and prevent sufficient improvement of hole-expandability. Therefore, the quantities of Mn and S must satisfy equation (3).

$$[Mg\%]\geq([O\%]/16\times0.8)\times24 \quad \ldots \ (1)$$

$$[S\%]\leq([Mg\%]/24-[O\%]/16\times0.8+0.00012)\times32 \quad \ldots \ (2)$$

$$[S\%]\leq0.0075/[Mn\%] \quad \ldots \ (3)$$

In order to relieve stress expansion during hole expansion and improve hole-expandability by forming fine uniform voids in the cross section of punched holes, it is important to achieve fine and uniform dispersion of (Nb, Ti)N. (Nb, Ti)N does not become the starting point for forming fine and uniform voids when too small in size and becomes the starting point for coarse cracks when too large.

It is considered that if the number of the precipitates is few, the number of fine voids formed during punching is too few to inhibit the occurrence of coarse cracks.

Through various studies the inventors discovered that combined precipitation of MgO and MgS can be used for achieving uniform and fine precipitation of (Nb, Ti)N. The inventors also discovered that not less than 3.0 μm and not more than 3.0 μm of the combined precipitates of MgO, MgS and (Nb, Ti)N must be present under the condition of not less than $5.0 \times 10^2/mm^2$ and not more than $1.0 \times 10^7/mm^2$ in order to achieve the desired effect of the combined precipitation. The presence of Al_2O_3 and SiO_2 in the composite oxides does not impair the effect. The presence of small quantities of MnS sulfide is not deleterious, too.

The dispersion condition of the composite precipitates specified by the present invention is quantified, for example, by the method described below. Replica specimens taken at random from the base steel

sheet are viewed through a transmission electron microscope (TEM), with a magnification of 5000 to 20000, over an area of at least 5000 μm^2, or preferably 50000μm^2. The number of the composite inclusions is counted and converted to the number per unit area.

The oxides and (Nb, Ti)N are identified by chemical composition analysis by energy dispersion X-ray spectroscopy (EDS) attached to TEM and crystal structure analysis of electron diffraction images taken by TEM. If it is too complicated to apply this identification to all of the composite inclusions determined, the following method may be applied for the sake of brevity.

First, the numbers of the composite inclusions are counted by shape and size by the method described above. Then, more than ten samples taken from the different shape and size groups are identified by the method described above and the ratios of the oxides and (Nb, Ti)N are determined. Then, the numbers of the inclusions determined first are multiplied by the ratios.

When carbides in steel interfere with said TEM observation, application of heat treatment to agglomerate, coarsen or melt the carbides facilitates the observation of the composite inclusions.

Si and Al are very important elements for the structure control to secure ductility. However, Si sometimes produces, in the hot-rolling process, surface irregularities called Si-scale which are detrimental to product appearance, formation of chemical treatment films and adherence of paints.

Therefore, plentiful addition of Si is undesirable when chemical treatability is critical. Compatibility between ductility and chemical treatability in such cases can be obtained by substituting Al for Si. If, however, the additions of both Si and Al are too much, the percentage of the ferrite phase becomes too great to provide the desired strength.

In order, therefore, to secure adequate strength and

ductility, the combined content of Si and Al must satisfy equation (4). Particularly when ductility is important, the combined content should preferably be not less than 0.9.

$$[Si\%]+2.2\times[Al\%]\geq 0.35 \quad \ldots (4)$$

Next, the structure of steel sheets according to the present invention will be described.

Being a technology to improve the cross-sectional properties to punched holes, the present invention produces the desired effect in steels whose structure contains any of ferrite, bainite and martensite.

However, steel structure must be controlled according to the required mechanical properties because steel structure affects mechanical properties.

(1) Steel Sheet Primarily Comprising Bainite (Steel Sheet B of the Present Invention)

In order to secure strength of over 980 MPa, it is necessary to strengthen the structure of steel. In order to enhance hole-expandability, among various workabilities, the steel structure must primarily comprise bainite.

It is preferable to contain ferrite as a second phase in order to enhance ductility. In the steel sheet B of the present invention, residual austenite does not mar the effect of the present invention, but coarse cementite and pearlite are undesirable because the presence thereof lessens the end-face properties improving effect of the Mg-precipitates.

Ductility and hole-expandability of steels whose strength exceeds 980 N/mm^2 deteriorate with increasing strength. In this connection, the inventors discovered that limiting the contents of C, Mn, Ti and Nb in steels primarily comprising bainite is effective for securing ductility while maintaining strength as well as the hole-expandability enhancing effect by the improvement of the end-face properties of punched holes by Mg-precipitates.

That is to say, the inventors derived the following

three equations by making the most of TiC precipitation strengthening and clarifying the effects of structure strengthening by Mn and C on steel properties, as explained below.

As the solid solution of Ti increases when the amount of C added is smaller than that of Ti, with a resulting deterioration of ductility, $0.9 \le 48/12 \times C/Ti$. If C content is greater than Ti content, TiC precipitates during hot-rolling, thereby marring the strength enhancing effect and deteriorating hole-expandability through the increase of C in the second phase.

As this leads to the lessening of the end-face properties improving effect of Mg-precipitates, $48/12 \times C/Ti$ should not be greater than 1.7.

That is to say, the Ti and C contents must satisfy equation (5).

$$0.9 \le 48/12 \times C/Ti < 1.7 \quad \ldots (5)$$

It is preferable $0.9 \le 48/12 \times C/Ti < 1.3$ particularly when hole-expandability is important.

As the amount of Mn addition increases, ferrite formation is inhibited and the percentage of the second phase increases, which, in turn, facilitates the securing of strength but brings about the lowering of ductility. Meanwhile, C hardens the second phase, thereby deteriorating hole-expandability and improving ductility.

In order, therefore, to secure the ductility required by the tensile-strength in excess of 980 N/mm^2, the C and Mn contents must satisfy equation (6).

$$50227 \times C - 4479 \times Mn > -9860 \quad \ldots (6)$$

In order to secure workability, it is necessary to satisfy the two equations given above. With steel sheets whose strength is of the order of 780 N/mm^2, it is relatively easy to satisfy the two equations while securing strength. In order to secure strength in excess of 980 N/mm^2, however, addition of C that deteriorates hole-expandability and Mn that deteriorates ductility is

inevitable.

In order to secure strength in excess of 980 N/mm^2, it is necessary to control steel composition within the range that satisfies equation (7) while satisfying the two equations given above.

$$811\times C+135\times Mn+602\times Ti+794\times Nb>465 \quad \ldots (7)$$

Next, the manufacturing method will be described.

In order to prevent ferrite formation and obtain good hole-expandability, finish-rolling must be completed at a temperature of not lower than the Ar_3 transformation point. It is, however, preferable, to complete finish-rolling at a temperature of not higher than 950 °C because steel structure coarsens, with a resulting lowering of strength and ductility.

In order to inhibit the formation of carbides deleterious to hole-expandability and obtain high hole-expandability, the cooling rate must be not less than 20 °C/s.

The coiling temperature must be not lower than 300 °C because hole-expandability deteriorates as a result of martensite formation therebelow.

The bainite formed at low temperatures, when present as the second phase, deteriorates hole-expandability, though not as much as is done by martensite. It is therefore preferable to coil the steel sheet at a temperature not lower than 350 °C.

The coiling temperature should be not higher than 600 °C because pearlite and cementite deleterious to hole-expandability are formed thereabove.

Air-cooling applied in the course of continuous cooling effectively enhances ductility by increasing the proportion of ferrite phase. However, air-cooling sometimes forms pearlite that lowers not only ductility and hole-expandability, depending on the temperature and time thereof.

The air-cooling temperature should be not lower than

650 °C because pearlite deleterious to hole-expandability is formed early therebelow.

If the air-cooling temperature is over 750 °C, on the other hand, ferrite formation delays to inhibit the attainment of the air cooling effect and expedites the formation of pearlite during subsequent cooling. Therefore, the air-cooling temperature is not higher than 750 °C.

Air-cooling for over 15 seconds not only saturates the increase of ferrite but also imposes a load on the control of the subsequent cooling rate and coiling temperature. Therefore, the air-cooling time is not longer than 15 seconds.

(2) Steel Sheet Primarily Comprising Ferrite and Martensite (Steel Sheet FM of the Present Invention)

In order to secure high ductility and hole-expandability, it is necessary to secure a ductile steel structure because the end-face controlling technology is a technology related to the enhancement of the hole-expandability of steel sheets. It is therefore necessary that steel structure primarily comprises ferrite and martensite.

In order to secure high ductility, it is preferable that ferrite content is not less than 50 %. While residual austenite does not bar the effect of the present invention in steel sheet FM, coarse cementite and pearlite, which lessen the end-face properties improving effect of Mg-precipitates, are undesirable.

In the hot-rolling process, the desired structure must be formed in a short time after finish-rolling, and steel composition strongly affects the formation of the desired structure. In order to enhance the ductility of steel whose structure primarily comprises ferrite and martensite, it is important to secure an adequate amount of ferrite.

In order to secure the adequate amount of ferrite effective for the enhancement of ductility, C, si, Mn and Al contents must satisfy equation (8) given below. If the value of equation (8) is smaller than -100, ductility deteriorates because an adequate amount of ferrite is not obtained and the percentage of the second phase increases.

$$-100 \leq -300[C\%]+105[Si\%]-95[Mn\%]+233[Al\%] \quad \ldots (8)$$

The inventors conducted studies to discover means to enhance ductility of steels whose structure primarily comprises ferrite and martensite without lessening the hole-expandability improving effect of Mg-precipitates through the improvement of the end-face properties of punched holes. Through the studies, the inventors discovered that control of the shape and particle size of ferrite is conducive to ductility enhancement, as explained below.

The shape of ferrite grains is one of the important indexes for the ductility enhancement of steel sheet FM according to the present invention. Generally, high-alloy steels contain many ferrite grains elongating in the rolling direction. Through studies, the inventors discovered that the elongated ferrite grains induce the deterioration of ductility and lowering the probability of presence of crystal grains having a short diameter (ds) to long diameter (dl) ratio (ds/dl) smaller than 0.1 is effective.

In order to ensure the enhancement of ductility by the control of ferrite grains, it is necessary that ferrite grains whose ds/dl ratio is not smaller than 0.1 account for not less than 80 % of all ferrite grains.

The size of ferrite grains is one of the most important indexes for the ductility enhancement according to the present invention. Generally, crystal grains grow smaller with increasing strength. Through studies the inventors discovered that, at the same strength level, sufficiently grown ferrite grains contribute to ductility

enhancement.

In order to ensure the enhancement of ductility, it is necessary that ferrite grains not smaller than 2 μm account for not less than 80 % of all ferrite grains.

Next, the manufacturing method will be described.

In order to prevent ferrite formation and obtain good hole-expandability, finish-rolling must be completed at a temperature of not lower than the Ar_3 transformation point. It is, however, preferable, to complete finish-rolling at a temperature not higher than 950 °C because steel structure coarsens, with a resulting lowering of strength and ductility. In order to inhibit the formation of carbides deleterious to hole-expandability and obtain high hole-expandability, the cooling rate must be not less than 20 °C/second.

Coiling temperature should be lower than 300 °C because martensite is not formed therebelow and, as a result, the desired strength becomes unobtainable. In order to secure adequate strength and achieve sufficient ductility improvement, it is preferable to coil at a temperature not higher than 200 °C.

Air-cooling applied in the course of continuous cooling effectively enhances ductility by increasing the proportion of ferrite phase. However, air-cooling sometimes forms pearlite that lowers not only ductility and hole-expandability, depending on the temperature and time thereof.

The air-cooling temperature should be not lower than 650 °C because pearlite deleterious to hole-expandability is formed early therebelow.

If the air-cooling temperature is over 750 °C, on the other hand, ferrite formation delays to inhibit the attainment of the air cooling effect and expedite the formation of pearlite during subsequent cooling. Therefore, the air-cooling temperature is not higher than 750 °C.

Air-cooling for over 15 seconds not only saturates the increase of ferrite but also imposes load on the control of the subsequent cooling rate and coiling temperature. Therefore, the air-cooling time is not longer than 15 seconds.

(3) Steel Sheet Primarily Comprising Ferrite and Bainite (Steel Sheet FB of the Present Invention)

Because the end-face controlling technology is a technology related to the enhancement of hole-expandability, hole-expandability is strongly affected by the ductility and hole-expandability (base properties) of the base metal. Steel sheets for such members as automobile suspensions that demand high hole-expandability should have a good balance between ductility and hole-expandability. Therefore, it is necessary to further enhance hole-expandability by using the end-face controlling technology.

In order to obtain higher hole-expandability, it is necessary that steel structure primarily comprises ferrite and bainite. It is preferable that ferrite content is not lower than 50 % because particularly high ductility is obtainable.

While residual austenite does not bar the effect of the present invention in steel sheet FB, coarse cementite and pearlite, which lessen the end-face properties improving effect of Mg-precipitates, are undesirable.

In the hot-rolling process, the desired structure must be formed in a short time after finish-rolling, and steel composition strongly affects the formation of the desired structure. In order to enhance the ductility of steel whose structure primarily comprises ferrite and bainite, it is important to secure an adequate amount of ferrite.

In order to secure the adequate amount of ferrite effective for the enhancement of ductility, C, Si, Mn and Al contents must satisfy equation (8) given below. If

the value of equation (8) is smaller than -100, ductility deteriorates because an adequate amount of ferrite is not obtained and the percentage of the second phase increases.

$$-100 \leq -300[C\%]+105[Si\%]-95[Mn\%]+233[Al\%] \quad \ldots (8)$$

The inventors conducted studies to discover means to enhance ductility of steels whose structure primarily comprises ferrite and martensite without lessening the hole-expandability improving effect of Mg-precipitates through the improvement of the end-face properties of punched holes. Through the studies, the inventors discovered that control of the shape and particle size of ferrite is conducive to ductility enhancement, as explained below.

The shape of ferrite grains is one of the important indexes for the ductility enhancement of steel sheet FM according to the present invention. Generally, high-alloy steels contain many ferrite grains elongating in the rolling direction. Through studies, the inventors discovered that the elongated ferrite grains induce the deterioration of ductility and lowering the probability of presence of crystal grains having a short diameter (ds) to long diameter (dl) ratio (ds/dl) smaller than 0.1 is effective.

In order to ensure the enhancement of ductility by the control of ferrite grains, it is necessary that ferrite grains whose ds/dl ratio is not smaller than 0.1 account for not less than 80 % of all ferrite grains.

The size of ferrite grains is one of the most important indexes for the ductility enhancement according to the present invention. Generally, crystal grains grow smaller with increasing strength. Through studies the inventors discovered that, at the same strength level, sufficiently grown ferrite grains contribute to ductility enhancement.

In order to ensure the enhancement of ductility, it is necessary that ferrite grains not smaller than 2 μm

account for not less than 80 % of all ferrite grains.

Next, the manufacturing method will be described.

In order to prevent ferrite formation and obtain good hole-expandability, finish-rolling must be completed at a temperature not lower than the Ar_3 transformation point. It is, however, preferable to complete finish-rolling at a temperature not higher than 950 °C because steel structure coarsens with a resulting lowering of strength and ductility.

In order to inhibit the formation of carbides deleterious to hole-expandability and obtain high hole-expandability, the cooling rate must be not less than 20 °C/s.

The coiling temperature must be not lower than 300 °C because hole-expandability deteriorates as a result of martensite formation therebelow.

The bainite formed at low temperatures, when present as the second phase, deteriorates hole-expandability, though not as much as is done by martensite. It is therefore preferable to coil the steel sheet at a temperature not lower than 350 °C.

The coiling temperature should be not higher than 600 °C because pearlite and cementite deleterious to hole-expandability are formed thereabove.

Air-cooling applied in the course of continuous cooling effectively enhances ductility by increasing the proportion of ferrite phase. However, air-cooling sometimes forms pearlite that lowers ductility and hole-expandability, depending on the temperature and time thereof.

The air-cooling temperature should be not lower than 650 °C because pearlite deleterious to hole-expandability is formed early therebelow.

If the air-cooling temperature is over 750 °C, on the other hand, ferrite formation delays to inhibit the attainment of the air cooling effect and expedite the

formation of pearlite during subsequent cooling. Therefore, the air-cooling temperature is not higher than 750 °C.

Air-cooling for over 15 seconds not only saturates the increase of ferrite but also imposes a load on the control of the subsequent cooling rate and coiling temperature. Therefore, the air-cooling time is not longer than 15 seconds.

Next, the present invention will be described by reference to examples thereof.

[Example 1]

Example 1 is one of the steels F according to the present invention.

Steels of compositions and properties shown in Tables 1 and 2 were prepared and continuously cast to slabs by the conventional process. Reference characters A to Z designate the steels whose compositions are according to the present invention, whereas reference characters a, b, c, e and f designate steels whose C, Mn, O, S and Mg contents, respectively, are outside the scope of the present invention.

Steels a, b, c, d, e, f and g, respectively, did not satisfy equation (5), equations (3) and (6), equations (1) and (2), equation (4), equations (2) and (3), equation (1), and equation (7). The number of precipitates in steel f was outside the scope of the present invention.

The steels were heated in a heating furnace at temperatures not lower than 1200 °C and then hot-rolled to sheets ranging in thickness from 2.6 to 3.2 mm. Tables 3 and 4 show the hot-rolling conditions.

In Tables 3 and 4, the cooling rates of A4 and J2, the air-cooling start temperatures of B3 and F3, and the coiling temperatures of E3, G3 and Q4 are outside the scope of the present invention.

Tensile tests and hole-expanding tests were performed on JIS No. 5 specimens taken from the hot-

rolled steel sheets thus obtained. Hole-expandability (λ) was evaluated by expanding a 10 mm diameter punched hole with a 60°-conical punch and using equation $\lambda = (d - dO)/dO \times 100$ wherein d = the hole diameter when a crack has penetrated through the sheet and dO is the initial hole diameter (10 mm).

Table 2 shows the tensile strength TS, elongation El and hole-expandabilityλ of the individual specimens. Figure 1 shows the relationship between strength and ductility and Figure 2 shows the relationship between strength and hole-expandability (ratio). It is obvious that the steels according to the present invention excel over the steels tested for comparison in either or both of ductility and hole-expandability (ratio). Steel g1 did not achieve the desired strength.

Thus, the present invention provides hot-rolled high-strength steel sheets excellent in both hole-expandability and ductility while securing the desired strength of 980 N/mm^2.

Table 1

Steel	C	Si	Mn	P	S	N	Mg	Al	Nb	Ti	Ca	O	Remarks
	mass %												
A	0.062	1.23	2.4	0.004	0.0010	0.005	0.0023	0.035	0.044	0.179	-	0.0014	Steel of the present invention
B	0.060	1.30	2.5	0.007	0.0020	0.003	0.0040	0.040	0.035	0.170	-	0.0015	Steel of the present invention
C	0.055	1.40	2.8	0.006	0.0025	0.003	0.0030	0.050	0.014	0.150	-	0.0012	Steel of the present invention
D	0.050	1.00	2.2	0.006	0.0010	0.004	0.0040	0.030	0.035	0.170	-	0.0015	Steel of the present invention
E	0.060	0.03	2.2	0.006	0.0028	0.004	0.0030	0.180	0.044	0.180	-	0.0010	Steel of the present invention
F	0.065	0.50	2.2	0.006	0.0028	0.004	0.0030	0.200	0.044	0.180	-	0.0010	Steel of the present invention
G	0.050	1.30	2.4	0.008	0.0025	0.004	0.0044	0.036	0.040	0.150	-	0.0011	Steel of the present invention
H	0.030	1.30	2.5	0.006	0.0020	0.003	0.0040	0.033	0.050	0.130	-	0.0015	Steel of the present invention
I	0.080	0.50	2.0	0.010	0.0035	0.004	0.0017	0.032	0.055	0.190	-	0.0008	Steel of the present invention
J	0.080	0.50	3.0	0.003	0.0018	0.002	0.0035	1.300	0.035	0.195	0.003	0.0015	Steel of the present invention
K	0.050	1.40	2.7	0.020	0.0025	0.003	0.0035	0.034	0.030	0.130	-	0.0015	Steel of the present invention
L	0.050	0.60	2.0	0.012	0.0035	0.003	0.0080	0.030	0.090	0.190	0.002	0.0007	Steel of the present invention
M	0.060	1.20	2.2	0.015	0.0030	0.002	0.0050	0.005	0.030	0.190	-	0.0040	Steel of the present invention
N	0.050	1.30	2.5	0.012	0.0020	0.003	0.0010	0.800	0.035	0.130	-	0.0007	Steel of the present invention
O	0.040	1.20	2.5	0.011	0.0025	0.002	0.0025	0.030	0.000	0.170	0.002	0.0012	Steel of the present invention
P	0.050	1.10	2.6	0.006	0.0025	0.004	0.0030	0.030	0.037	0.124	0.002	0.0014	Steel of the present invention
Q	0.050	1.10	2.6	0.009	0.0020	0.005	0.0030	0.037	0.030	0.140	-	0.0010	Steel of the present invention
R	0.055	0.10	2.6	0.006	0.0025	0.002	0.0029	0.450	0.030	0.140	0.002	0.0015	Steel of the present invention
S	0.055	0.50	2.6	0.009	0.0020	0.002	0.0022	0.200	0.035	0.140	-	0.0015	Steel of the present invention
T	0.070	0.90	2.2	0.008	0.0030	0.002	0.0040	0.035	0.040	0.170	0.002	0.0025	Steel of the present invention
U	0.070	0.95	2.2	0.008	0.0030	0.002	0.0035	0.035	0.070	0.170	0.002	0.0025	Steel of the present invention
V	0.070	1.30	2.2	0.070	0.0025	0.002	0.0030	0.040	0.035	0.155	0.002	0.0015	Steel of the present invention
W	0.050	1.30	2.4	0.007	0.0025	0.003	0.0040	0.034	0.040	0.155	-	0.0015	Steel of the present invention
X	0.060	1.20	2.3	0.017	0.0030	0.003	0.0020	0.080	0.030	0.170	0.002	0.0015	Steel of the present invention
Y	0.060	0.90	2.3	0.017	0.0030	0.002	0.0032	0.000	0.030	0.150	-	0.0015	Steel of the present invention
Z	0.060	0.90	2.3	0.016	0.0030	0.002	0.0035	0.033	0.025	0.170	-	0.0015	Steel of the present invention
a	0.210	1.30	2.2	0.120	0.0030	0.002	0.0031	0.005	0.030	0.080	0.002	0.0015	Steel for Comparison
b	0.050	1.00	3.6	0.020	0.0025	0.002	0.0040	0.030	0.030	0.170	-	0.0015	Steel for Comparison
c	0.060	1.00	2.2	0.020	0.0030	0.002	0.0030	0.035	0.035	0.170	0.002	0.0060	Steel for Comparison
d	0.050	0.20	2.5	0.010	0.0028	0.002	0.0029	0.030	0.030	0.150	0.002	0.0015	Steel for Comparison
e	0.055	1.10	2.5	0.010	0.0100	0.002	0.0040	0.020	0.020	0.150	0.002	0.0015	Steel for Comparison
f	0.070	0.90	2.2	0.010	0.0015	0.002	0.0003	0.025	0.025	0.170	0.002	0.0015	Steel for Comparison
g	0.070	0.90	1.4	0.010	0.0020	0.002	0.0040	0.030	0.030	0.170	0.002	0.0007	Steel for Comparison

Table 2

Steel	Right-hand side of equation 1	Right-hand side of equation 2	Right-hand side of equation 3	Left-hand side of equation 4	Middle side of equation 5	Left-hand side of equation 6	Left-hand side of equation 7	Number of precipitates/mm^2	Ar_3 °C	Remarks
A	0.0017	0.0047	0.0031	1.31	1.39	-7815	522	2.1E+03	743	Steel of the present invention
B	0.0018	0.0068	0.0030	1.39	1.41	-8184	516	4.3E+03	743	Steel of the present invention
C	0.0014	0.0059	0.0027	1.51	1.47	-9779	524	3.7E+03	729	Steel of the present invention
D	0.0018	0.0068	0.0034	1.07	1.18	-7342	468	3.8E+03	759	Steel of the present invention
E	0.0012	0.0062	0.0034	0.43	1.33	-6840	489	3.9E+03	728	Steel of the present invention
F	0.0012	0.0062	0.0034	0.94	1.44	-6589	493	3.9E+03	738	Steel of the present invention
G	0.0013	0.0079	0.0031	1.38	1.33	-8238	487	5.1E+03	755	Steel of the present invention
H	0.0018	0.0068	0.0030	1.37	0.92	-9691	480	4.3E+03	758	Steel of the present invention
I	0.0010	0.0048	0.0038	0.57	1.68	-4940	493	3.1E+03	744	Steel of the present invention
J	0.0018	0.0061	0.0025	3.36	1.64	-9419	615	3.7E+03	679	Steel of the present invention
K	0.0018	0.0061	0.0028	1.47	1.54	-9582	507	4.0E+03	741	Steel of the present invention
L	0.0008	0.0134	0.0038	0.67	1.05	-6447	496	9.4E+03	762	Steel of the present invention
M	0.0048	0.0041	0.0034	1.21	1.26	-6840	484	4.5E+03	761	Steel of the present invention
N	0.0008	0.0041	0.0030	3.06	1.54	-8686	484	1.7E+03	749	Steel of the present invention
O	0.0014	0.0053	0.0030	1.27	0.94	-9188	472	3.2E+03	751	Steel of the present invention
P	0.0017	0.0056	0.0029	1.17	1.61	-9134	496	3.6E+03	736	Steel of the present invention
Q	0.0012	0.0062	0.0029	1.18	1.43	-9134	500	3.5E+03	737	Steel of the present invention
R	0.0018	0.0053	0.0029	1.09	1.57	-8883	504	3.4E+03	707	Steel of the present invention
S	0.0018	0.0044	0.0029	0.94	1.57	-8883	508	2.5E+03	718	Steel of the present invention
T	0.0030	0.0052	0.0034	0.98	1.65	-6338	488	4.3E+03	747	Steel of the present invention
U	0.0030	0.0045	0.0034	1.03	1.65	-6338	512	3.8E+03	748	Steel of the present invention
V	0.0018	0.0054	0.0034	1.39	1.81	-6338	475	3.5E+03	771	Steel of the present invention
W	0.0018	0.0068	0.0031	1.37	1.29	-8238	490	4.5E+03	754	Steel of the present invention
X	0.0018	0.0041	0.0033	1.38	1.41	-7288	485	2.8E+03	755	Steel of the present invention
Y	0.0018	0.0057	0.0033	0.90	1.60	-7288	473	4.0E+03	747	Steel of the present invention
Z	0.0018	0.0061	0.0033	0.97	1.41	-7288	481	4.3E+03	747	Steel of the present invention
a	0.0018	0.0056	0.0034	1.31	10.50	694	539	3.9E+03	712	Steel for Comparison
b	0.0018	0.0068	0.0021	1.07	1.18	-13613	653	4.5E+03	673	Steel for Comparison
c	0.0072	-0.0018	0.0034	1.08	1.41	-6840	476	1.5E+03	757	Steel for Comparison
d	0.0018	0.0053	0.0030	0.27	1.33	-8686	492	3.6E+03	719	Steel for Comparison
e	0.0018	0.0068	0.0030	1.17	1.47	-8435	488	8.3E+03	741	Steel for Comparison
f	0.0018	0.0018	0.0034	0.97	1.65	-6338	476	3.0E+02	747	Steel for Comparison
g	0.0008	0.0081	0.0054	0.97	1.65	-2755	372	4.7E+03	798	Steel for Comparison

* Provided, however, that $Ar_3=896-509(C\%)+26.9(Si\%)-63.5(Mn\%)+229(P\%)$

Table 3

Steel	Finishing Temperature	Cooling Rate	Air-cooling Start Temperature	Air-cooling Time	Coiling Temperature	Tensile Strength	Elongation	Hole-Expandability	Remarks
	°C	°C/s	°C	s	°C	N/mm^2	%	%	
A1	920	70	680	4	490	1050	14	64	Steel of the present invention
A2	910	70	720	2	580	1095	15	52	Steel of the present invention
A3	920	40	-	-	500	1067	14	69	Steel of the present invention
A4	930	10	-	-	480	1057	9	41	Steel for Comparison
B1	920	70	670	5	490	1044	14	64	Steel of the present invention
B2	900	70	720	2	300	1019	14	65	Steel of the present invention
B3	910	70	780	3	500	1061	10	63	Steel for Comparison
B4	890	40	-	-	500	1073	14	65	Steel of the present invention
C1	910	70	670	3	500	1053	12	62	Steel of the present invention
C2	920	40	-	-	480	1055	12	67	Steel of the present invention
D1	890	70	670	4	490	993	16	74	Steel of the present invention
D2	930	70	680	3	550	1023	16	69	Steel of the present invention
E1	930	70	670	3	500	1004	16	68	Steel of the present invention
E2	920	40	-	-	480	1006	16	71	Steel of the present invention
E3	920	70	720	3	620	1076	15	40	Steel for Comparison
F1	910	70	680	3	500	1013	16	64	Steel of the present invention
F2	910	40	-	-	500	1025	16	64	Steel of the present invention
F3	890	70	630	4	500	1025	10	43	Steel for Comparison
G1	920	70	680	3	500	1015	14	67	Steel of the present invention
G2	920	70	-	-	480	1017	14	72	Steel of the present invention
G3	930	40	-	-	620	1087	14	39	Steel for Comparison
H1	910	70	690	3	480	1008	13	87	Steel of the present invention
H2	900	40	-	-	480	1020	13	91	Steel of the present invention
I1	920	70	680	3	520	1013	18	58	Steel of the present invention
I2	910	40	-	-	500	1015	18	61	Steel of the present invention
J1	880	70	670	4	500	1135	12	55	Steel of the present invention
J2	870	10	-	-	500	1147	7	39	Steel for Comparison
K1	910	70	670	4	450	1036	13	61	Steel of the present invention
K2	890	70	680	4	550	1098	13	52	Steel of the present invention
L1	890	70	670	3	500	1017	16	79	Steel of the present invention
L2	910	40	-	-	550	1054	17	73	Steel of the present invention
M1	890	70	670	3	480	1011	16	70	Steel of the present invention
M2	890	50	680	3	500	1021	16	69	Steel of the present invention
N1	880	70	680	3	500	1012	14	61	Steel of the present invention
N2	890	30	-	-	500	1024	14	64	Steel of the present invention

Table 4 (Continued from Table 3)

Steel	Finishing Temperature	Cooling Rate	Air-cooling Start Temperature	Air-cooling Time	Coiling Temperature	Tensile Strength	Elongation	Hole-Expandability	Remarks
	°C	°C/s	°C	s	°C	N/mm²	%	%	
O1	920	70	670	5	500	999	14	87	Steel of the present invention
O2	910	70	690	3	480	991	14	87	Steel of the present invention
P1	890	70	680	3	480	1022	13	59	Steel of the present invention
P2	900	70	700	4	500	1032	13	59	Steel of the present invention
Q1	900	70	670	4	500	1026	13	64	Steel of the present invention
Q2	890	150	660	5	480	1016	14	64	Steel of the present invention
Q3	910	40	-	-	480	1028	13	69	Steel of the present invention
Q4	920	40	-	-	200	993	14	40	Steel for Comparison
R1	920	70	680	3	500	1020	14	60	Steel of the present invention
R2	920	40	-	-	500	1032	14	66	Steel of the present invention
S1	930	100	660	5	500	1028	14	60	Steel of the present invention
S2	910	70	720	2	480	1018	14	60	Steel of the present invention
T1	900	70	680	3	480	1012	16	59	Steel of the present invention
T2	910	40	-	-	500	1034	16	60	Steel of the present invention
U1	890	70	680	4	480	1036	16	58	Steel of the present invention
U2	890	40	-	-	480	1048	16	60	Steel of the present invention
V1	890	70	660	3	520	1003	16	56	Steel of the present invention
V2	900	70	660	4	400	993	17	56	Steel of the present invention
V3	890	40	-	-	550	1030	17	61	Steel of the present invention
W1	920	70	700	3	500	1018	14	69	Steel of the present invention
W2	930	70	660	3	580	1058	15	62	Steel of the present invention
W3	910	40	-	-	480	1020	14	74	Steel of the present invention
X1	900	70	690	3	500	1012	15	65	Steel of the present invention
X2	930	70	-	-	480	1002	16	68	Steel of the present invention
Y1	890	70	680	4	480	997	16	61	Steel of the present invention
Y2	910	70	690	3	400	992	16	61	Steel of the present invention
Z1	910	70	670	3	500	1005	15	65	Steel of the present invention
Z2	910	70	680	3	400	995	16	66	Steel of the present invention
a1	850	70	680	3	480	1067	7	10	Steel for Comparison
b1	900	70	680	4	480	1178	5	51	Steel for Comparison
c1	920	70	680	3	500	1001	16	45	Steel for Comparison
d1	900	70	670	4	480	1009	6	68	Steel for Comparison
e1	900	70	680	3	480	1014	14	43	Steel for Comparison
f1	910	70	680	4	520	1000	17	39	Steel for Comparison
g1	910	70	680	3	500	896	19	44	Steel for Comparison

[Example 2]

Example 1 is one of the steels FM according to the present invention.

Steels of compositions and properties shown in Tables 5 and 6 were prepared and continuously cast to slabs by the conventional process. Reference characters A to Z designate the steels whose compositions are according to the present invention, whereas reference characters a, b, c, e and f designate steels whose C, Mn, O, S and Mg contents, respectively, are outside the scope of the present invention.

Steels b, c, d, e and f, respectively, did not satisfy equations (3) and (8), equations (1) and (2), equation (4), equations (2) and (3), equation (1), and equation (7). The number of precipitates in steels f and g was outside the scope of the present invention.

The steels were heated in a heating furnace at a temperatures not lower than 1200 °C and then hot-rolled to sheets ranging in thickness from 2.6 to 3.2 mm. Tables 7 and 8 show the hot-rolling conditions.

In Tables 7 and 8, the cooling rates of A4 and J2, the air-cooling start temperatures of B3 and F3, and the coiling temperatures of E3, G3 and Q4 are outside the scope of the present invention.

Tensile tests and hole-expanding tests were performed on JIS No. 5 specimens taken from the hot-rolled steel sheets thus obtained. Hole-expandability (λ) was evaluated by expanding a 10 mm diameter punched hole with a 60°-conical punch and using equation $\lambda = (d - dO)/dO \times 100$ wherein d = the hole diameter when crack has penetrated through the sheet and dO is the initial hole diameter (10 mm).

Tables 7 and 8 show the tensile strength TS, elongation El and hole-expandability λ of the individual specimens. Figure 3 shows the relationship between strength and ductility and Figure 4 shows the

relationship between strength and hole-expandability (ratio). It is obvious that the steels according to the present invention excel over the steels tested for comparison in either or both of ductility and hole-expandability (ratio).

Table 9 and Figure 5 show the relationship between ductility and the ratio at which the ratio (ds/dl) of short diameter (ds) to long diameter (dl) exceeds 0.1. It is obvious that high ductility is stably obtainable when the ratio is not less than 80 %.

Table 10 and Figure 6 show the relationship between ductility and the ratio of ferrite grains not smaller than 2 μm in all ferrite grains. It is obvious that high ductility is stably obtainable when the ratio is not less than 80 %.

Thus, the present invention provides hot-rolled high-strength steel sheets excellent in both hole-expandability and ductility.

Table 5

Steel	C	Si	Mn	P	S	N	Mg	Al	Nb	Ti	Ca	O	Remarks
	mass %												
A	0.060	0.88	1.2	0.018	0.0030	0.003	0.0030	0.040	0.000	0.025	-	0.0015	Steel of the present invention
B	0.055	0.87	1.2	0.011	0.0023	0.003	0.0040	0.028	0.000	0.020	-	0.0007	Steel of the present invention
C	0.060	0.80	1.2	0.015	0.0040	0.003	0.0020	0.005	0.000	0.020	-	0.0015	Steel of the present invention
D	0.060	0.85	1.1	0.005	0.0020	0.004	0.0040	0.002	0.000	0.025	-	0.0015	Steel of the present invention
E	0.060	0.03	1.2	0.006	0.0028	0.004	0.0023	0.180	0.000	0.025	-	0.0010	Steel of the present invention
F	0.065	0.50	1.2	0.006	0.0028	0.004	0.0023	0.200	0.000	0.025	-	0.0010	Steel of the present invention
G	0.060	1.60	1.5	0.011	0.0015	0.003	0.0030	0.042	0.000	0.020	-	0.0015	Steel of the present invention
H	0.060	0.90	1.4	0.007	0.0037	0.003	0.0035	0.032	0.000	0.020	-	0.0015	Steel of the present invention
I	0.070	1.00	1.3	0.010	0.0044	0.004	0.0017	0.032	0.000	0.030	-	0.0008	Steel of the present invention
J	0.170	1.00	3.3	0.030	0.0018	0.002	0.0035	1.300	0.000	0.025	-	0.0015	Steel of the present invention
K	0.060	1.30	2.0	0.020	0.0030	0.003	0.0035	0.034	0.000	0.025	-	0.0015	Steel of the present invention
L	0.065	0.50	0.7	0.012	0.0085	0.002	0.0080	0.030	0.000	0.035	-	0.0007	Steel of the present invention
M	0.060	1.20	1.4	0.015	0.0030	0.002	0.0050	0.005	0.000	0.190	-	0.0040	Steel of the present invention
N	0.060	1.40	1.5	0.012	0.0020	0.003	0.0010	0.800	0.000	0.020	-	0.0007	Steel of the present invention
O	0.070	1.20	1.4	0.011	0.0030	0.002	0.0025	0.030	0.000	0.020	0.002	0.0012	Steel of the present invention
P	0.130	0.92	1.6	0.006	0.0035	0.004	0.0023	0.030	0.020	0.000	0.002	0.0014	Steel of the present invention
Q	0.060	1.00	1.6	0.015	0.0035	0.005	0.0017	0.037	0.010	0.010	-	0.0010	Steel of the present invention
R	0.080	0.10	1.6	0.011	0.0040	0.001	0.0029	0.450	0.000	0.025	0.002	0.0015	Steel of the present invention
S	0.050	0.50	1.6	0.015	0.0030	0.002	0.0022	0.200	0.000	0.025	-	0.0015	Steel of the present invention
T	0.060	0.90	1.4	0.015	0.0030	0.002	0.0040	0.035	0.000	0.020	-	0.0025	Steel of the present invention
U	0.035	0.95	1.4	0.012	0.0030	0.002	0.0035	0.035	0.000	0.025	-	0.0025	Steel of the present invention
V	0.040	1.00	1.5	0.070	0.0030	0.002	0.0030	0.040	0.000	0.020	0.002	0.0015	Steel of the present invention
W	0.060	1.00	1.2	0.008	0.0025	0.003	0.0040	0.034	0.000	0.020	-	0.0015	Steel of the present invention
X	0.060	1.20	0.8	0.017	0.0030	0.003	0.0020	0.080	0.000	0.020	0.002	0.0015	Steel of the present invention
Y	0.065	0.90	1.2	0.017	0.0030	0.002	0.0032	0.000	0.000	0.025	-	0.0015	Steel of the present invention
Z	0.060	0.90	1.9	0.016	0.0030	0.002	0.0035	0.033	0.000	0.025	-	0.0015	Steel of the present invention
a	0.210	0.80	1.4	0.120	0.0030	0.002	0.0031	0.005	0.000	0.020	0.002	0.0015	Steel for Comparison
b	0.060	0.80	3.6	0.020	0.0025	0.002	0.0040	0.030	0.000	0.020	-	0.0015	Steel for Comparison
c	0.060	1.00	1.2	0.020	0.0030	0.002	0.0030	0.035	0.000	0.020	-	0.0060	Steel for Comparison
d	0.055	0.20	1.1	0.020	0.0040	0.002	0.0029	0.030	0.000	0.020	-	0.0015	Steel for Comparison
e	0.056	0.80	1.1	0.020	0.0100	0.002	0.0040	0.030	0.000	0.020	-	0.0015	Steel for Comparison
f	0.060	0.80	1.2	0.020	0.0015	0.002	0.0003	0.030	0.000	0.020	0.002	0.0015	Steel for Comparison
g	0.060	0.90	1.2	0.020	0.0040	0.002	0.0010	0.030	0.000	0.020	0.002	0.0007	Steel for Comparison

Table 6

Steel	Right-hand side of equation 1	Right-hand side of equation 2	Right-hand side of equation 3	Left-hand side of equation 4	Middle side of equation 8	Number of precipitates/mm^2	Ar_3 °C	Remarks
A	0.0018	0.0054	0.0061	0.97	-33	3.8E+03	815	Steel of the present invention
B	0.0008	0.0081	0.0061	0.93	-35	4.8E+03	816	Steel of the present invention
C	0.0018	0.0041	0.0063	0.81	-47	3.3E+03	814	Steel of the present invention
D	0.0018	0.0068	0.0068	0.85	-33	4.3E+03	819	Steel of the present invention
E	0.0012	0.0053	0.0061	0.43	-89	3.2E+03	790	Steel of the present invention
F	0.0012	0.0053	0.0061	0.94	-36	3.2E+03	800	Steel of the present invention
G	0.0018	0.0054	0.0050	1.69	17	3.0E+03	815	Steel of the present invention
H	0.0018	0.0061	0.0054	0.97	-49	4.6E+03	802	Steel of the present invention
I	0.0010	0.0048	0.0058	1.07	-32	3.5E+03	807	Steel of the present invention
J	0.0018	0.0061	0.0023	3.86	43	3.7E+03	633	Steel of the present invention
K	0.0018	0.0061	0.0038	1.37	-64	4.3E+03	778	Steel of the present invention
L	0.0008	0.0134	0.0107	0.57	-27	1.2E+04	835	Steel of the present invention
M	0.0048	0.0041	0.0054	1.21	-24	4.5E+03	812	Steel of the present invention
N	0.0008	0.0041	0.0050	3.16	173	1.7E+03	810	Steel of the present invention
O	0.0014	0.0053	0.0054	1.27	-21	3.4E+03	806	Steel of the present invention
P	0.0017	0.0047	0.0047	0.99	-87	3.4E+03	754	Steel of the present invention
Q	0.0012	0.0045	0.0047	1.08	-56	3.0E+03	794	Steel of the present invention
R	0.0018	0.0053	0.0047	1.09	-61	4.2E+03	759	Steel of the present invention
S	0.0018	0.0044	0.0047	0.94	-68	3.0E+03	786	Steel of the present invention
T	0.0030	0.0052	0.0054	0.98	-48	4.3E+03	804	Steel of the present invention
U	0.0030	0.0045	0.0054	1.03	-36	3.8E+03	817	Steel of the present invention
V	0.0018	0.0054	0.0050	1.09	-40	3.8E+03	823	Steel of the present invention
W	0.0018	0.0068	0.0063	1.07	-19	4.5E+03	818	Steel of the present invention
X	0.0018	0.0041	0.0094	1.38	51	2.8E+03	851	Steel of the present invention
Y	0.0018	0.0057	0.0063	0.90	-39	4.0E+03	815	Steel of the present invention
Z	0.0018	0.0061	0.0039	0.97	-96	4.3E+03	773	Steel of the present invention
a	0.0018	0.0056	0.0054	0.81	-111	3.9E+03	749	Steel for Comparison
b	0.0018	0.0068	0.0021	0.87	-269	4.5E+03	663	Steel for Comparison
c	0.0072	-0.0018	0.0063	1.08	-19	1.5E+03	821	Steel for Comparison
d	0.0018	0.0053	0.0068	0.27	-93	4.2E+03	808	Steel for Comparison
e	0.0018	0.0068	0.0068	0.87	-30	8.3E+03	824	Steel for Comparison
f	0.0018	0.0018	0.0063	0.87	-41	2.0E+02	815	Steel for Comparison
g	0.0008	0.0041	0.0063	0.97	-31	2.5E+02	818	Steel for Comparison

* Provided, however, that Ar_3=896-509(C%)+26.9(Si%)-63.5(Mn%)+229(P%)

Table 7

Steel	Finishing Temperature	Cooling Rate	Air-cooling Start Temperature	Air-cooling Time	Coiling Temperature	Tensile Strength	Elongation	Hole-Expandability	Remarks
	°C	°C/s	°C	s	°C	N/mm^2	%	%	
A1	920	70	680	4	100	608	33	80	Steel of the present invention
A2	910	70	720	2	250	588	31	98	Steel of the present invention
A3	920	40	-	-	100	618	30	83	Steel of the present invention
A4	930	10	-	-	100	608	25	50	Steel for Comparison
B1	920	70	670	5	100	603	32	81	Steel of the present invention
B2	900	70	720	2	250	593	31	97	Steel of the present invention
B3	910	70	780	3	100	608	25	74	Steel for Comparison
B4	890	40	-	-	100	608	31	84	Steel of the present invention
C1	910	70	670	3	100	578	33	85	Steel of the present invention
C2	920	40	-	-	100	590	31	86	Steel of the present invention
D1	890	70	670	4	100	606	32	84	Steel of the present invention
D2	930	70	680	3	250	591	31	98	Steel of the present invention
E1	930	70	670	3	100	548	34	89	Steel of the present invention
E2	920	40	-	-	100	558	33	91	Steel of the present invention
E3	920	70	720	3	350	533	25	106	Steel for Comparison
F1	910	70	680	3	100	584	33	84	Steel of the present invention
F2	910	40	-	-	100	596	31	86	Steel of the present invention
F3	890	70	630	4	100	584	25	55	Steel for Comparison
G1	920	70	680	3	100	791	25	54	Steel of the present invention
G2	920	70	-	-	100	803	23	56	Steel of the present invention
G3	930	40	-	-	350	783	20	70	Steel for Comparison
H1	910	70	690	3	100	607	32	81	Steel of the present invention
H2	900	40	-	-	100	619	30	82	Steel of the present invention
I1	920	70	680	3	100	619	32	79	Steel of the present invention
I2	910	40	-	-	100	631	30	81	Steel of the present invention
J1	880	70	670	4	100	973	19	29	Steel of the present invention
J2	870	10	-	-	100	985	13	15	Steel for Comparison
K1	910	70	670	4	100	738	27	65	Steel of the present invention
K2	890	70	680	4	250	723	26	79	Steel of the present invention
L1	890	70	670	3	100	583	33	84	Steel of the present invention
L2	910	40	-	-	250	568	32	101	Steel of the present invention
M1	890	70	670	3	100	945	20	32	Steel of the present invention
M2	890	50	680	3	100	945	20	32	Steel of the present invention
N1	880	70	680	3	100	673	30	71	Steel of the present invention
N2	890	30	-	-	100	685	27	73	Steel of the present invention

Table 8 (Continued from Table 7)

Steel	Finishing Temperature	Cooling Rate	Air-cooling Start Temperature	Air-cooling Time	Coiling Temperature	Tensile Strength	Elongation	Hole-Expandability	Remarks
	°C	°C/s	°C	s	°C	N/mm^2	%	%	
01	920	70	670	5	100	642	32	70	Steel of the present invention
02	910	70	690	3	100	642	31	76	Steel of the present invention
P1	890	70	680	3	100	676	30	74	Steel of the present invention
P2	900	70	700	4	100	676	30	72	Steel of the present invention
Q1	900	70	670	4	100	641	31	73	Steel of the present invention
Q2	890	150	660	5	100	641	32	72	Steel of the present invention
Q3	910	40	-	-	100	653	29	77	Steel of the present invention
Q4	920	40	-	-	350	611	23	95	Steel for Comparison
R1	920	70	680	3	100	779	26	53	Steel of the present invention
R2	920	40	-	-	100	791	24	59	Steel of the present invention
S1	930	100	660	5	100	609	33	77	Steel of the present invention
S2	910	70	720	2	100	609	30	84	Steel of the present invention
T1	900	70	680	3	100	615	32	79	Steel of the present invention
T2	910	40	-	-	100	627	30	81	Steel of the present invention
U1	890	70	680	4	100	616	32	79	Steel of the present invention
U2	890	40	-	-	100	628	30	79	Steel of the present invention
V1	890	70	660	3	100	622	32	78	Steel of the present invention
V2	900	70	660	4	250	602	31	96	Steel of the present invention
V3	890	40	-	-	100	630	30	81	Steel of the present invention
W1	920	70	700	3	100	610	32	80	Steel of the present invention
W2	930	70	660	3	250	590	31	98	Steel of the present invention
W3	910	40	-	-	100	602	31	87	Steel of the present invention
X1	900	70	690	3	100	582	33	85	Steel of the present invention
X2	930	70	-	-	100	587	31	84	Steel of the present invention
Y1	890	70	680	4	100	609	32	81	Steel of the present invention
Y2	910	70	690	3	250	589	31	98	Steel of the present invention
Z1	910	70	670	3	100	670	30	71	Steel of the present invention
Z2	910	70	680	3	250	645	29	90	Steel of the present invention
a1	850	70	680	3	100	683	20	40	Steel for Comparison
b1	900	70	680	4	100	815	18	51	Steel for Comparison
c1	920	70	680	3	100	604	31	40	Steel for Comparison
d1	900	70	670	4	100	523	25	92	Steel for Comparison
e1	900	70	680	3	100	493	34	45	Steel for Comparison
f1	910	70	680	4	100	608	29	50	Steel for Comparison
g1	910	70	680	3	100	516	33	50	Steel for Comparison

Table 9

Steel	Finishing Temperature °C	Cooling Rate °C/s	Cooling Start Temperature °C	Air-cooling Time s	Coiling Temperature °C	Tensile Strength N/mm^2	Ratio of ds/dl ≥ 0.1	Elongation %	Hole-Expandability %	Remarks
A1	920	70	680	4	100	608	91%	33	80	Steel of the present invention
A5	920	70	780	4	100	609	40%	24	80	Steel for Comparison
A6	920	70	760	4	100	610	70%	25	80	Steel for Comparison
A7	920	70	740	4	100	605	82%	32	81	Steel of the present invention
A8	920	80	720	4	100	605	88%	33	81	Steel of the present invention
A9	920	80	700	4	100	606	90%	33	81	Steel of the present invention
A10	920	80	660	4	100	611	92%	33	80	Steel of the present invention

Table 10

Steel	Finishing Temperature	Cooling Rate	Cooling Start Temperature	Air-cooling Time	Coiling Temperature	Tensile Strength	Ratio of Ferrite Grains Not Smaller Than 2 μm	Elongation	Hole-Expandability	Remarks
	°C	°C/s	°C	s	°C	N/mm²		%	%	
B1	920	70	670	5	100	603	88	32	81	Steel of the present invention
B5	860	70	670	4	100	603	50	25	81	Steel for Comparison
B6	880	70	670	4	100	601	68	26	81	Steel for Comparison
B7	880	70	730	4	100	600	83	32	81	Steel of the present invention
B8	920	70	730	5	100	603	90	33	81	Steel of the present invention
B9	960	80	670	6	100	605	93	33	81	Steel of the present invention
B10	960	80	730	6	100	605	94	33	81	Steel of the present invention

[Example 3]

Example 3 is one of the steels FB according to the present invention.

Steels of compositions and properties shown in Tables 11 and 12 were prepared and continuously cast to slabs by the conventional process. Reference characters A to Z designate the steels whose compositions are according to the present invention, whereas reference characters a, b, c, e and f designate steels whose C, Mn, O, S and Mg contents, respectively, are outside the scope of the present invention.

Steels b, c, d, e and f, respectively, did not satisfy equations (3) and (8), equations (1) and (2), equation (4) and (8), equations (2) and (3), and equation (1). The number of precipitates in steels f and g was outside the scope of the present invention.

The steels were heated in a heating furnace at temperatures not lower than 1200 °C and then hot-rolled to sheets ranging in thickness from 2.6 to 3.2 mm. Tables 13 and 14 show the hot-rolling conditions.

In Tables 13 and 14, the cooling rates of A4 and J2, the air-cooling start temperatures of B3 and F3, and the coiling temperatures of E3, G3 and Q4 are outside the scope of the present invention.

Tensile tests and hole-expanding tests were performed on JIS No. 5 specimens taken from the hot-rolled steel sheets thus obtained. Hole-expandability (λ) was evaluated by expanding a 10 mm diameter punched hole with a 60°-conical punch and using equation $\lambda = (d - dO)/dO \times 100$ wherein d = the hole diameter when crack has penetrated through the sheet and dO is the initial hole diameter (10 mm).

Tables 13 and 14 show the tensile strength TS, elongation El and hole-expandability λ of the individual specimens. Figure 7 shows the relationship between strength and ductility and Figure 8 shows the

relationship between strength and hole-expandability (ratio). It is obvious that the steels according to the present invention excel over the steels tested for comparison in either or both of ductility and hole-expandability (ratio).

Table 15 and Figure 9 show the relationship between ductility and the ratio at which the ratio (ds/dl) of short diameter (ds) to long diameter (dl) exceeds 0.1. It is obvious that high ductility is stably obtainable when the ratio is not less than 80 %.

Table 16 and Figure 10 show the relationship between ductility and the ratio of ferrite grains not smaller than 2 μm in all ferrite grains. It is obvious that high ductility is stably obtainable when the ratio is not less than 80 %.

Thus, the present invention provides hot-rolled high-strength steel sheets excellent in both hole-expandability and ductility.

Table 11

Steel	C	Si	Mn	P	S	N	Mg	Al	Nb	Ti	Ca	O	Remarks
	mass %												
A	0.039	0.92	1.2	0.006	0.0028	0.004	0.0023	0.030	0.037	0.124	-	0.0014	Steel of the present invention
B	0.030	1.00	1.3	0.009	0.0032	0.005	0.0017	0.037	0.022	0.152	-	0.0010	Steel of the present invention
C	0.032	1.00	1.2	0.015	0.0040	0.003	0.0020	0.005	0.028	0.150	-	0.0015	Steel of the present invention
D	0.040	0.90	1.4	0.005	0.0020	0.004	0.0040	0.002	0.042	0.140	-	0.0015	Steel of the present invention
E	0.039	0.03	1.2	0.006	0.0028	0.004	0.0023	0.180	0.037	0.124	-	0.0010	Steel of the present invention
F	0.039	0.50	1.2	0.006	0.0028	0.004	0.0023	0.200	0.037	0.124	-	0.0010	Steel of the present invention
G	0.040	0.95	2.0	0.008	0.0019	0.002	0.0044	0.036	0.036	0.081	-	0.0011	Steel of the present invention
H	0.035	0.90	2.0	0.007	0.0037	0.003	0.0035	0.033	0.032	0.083	-	0.0015	Steel of the present invention
I	0.030	1.00	1.3	0.010	0.0044	0.004	0.0017	0.032	0.028	0.160	-	0.0008	Steel of the present invention
J	0.170	0.50	3.3	0.030	0.0018	0.002	0.0035	1.300	0.035	0.100	0.003	0.0015	Steel of the present invention
K	0.050	1.30	2.0	0.020	0.0030	0.003	0.0035	0.034	0.030	0.050	-	0.0015	Steel of the present invention
L	0.030	0.60	0.7	0.012	0.0085	0.003	0.0080	0.030	0.035	0.090	0.002	0.0007	Steel of the present invention
M	0.060	1.20	1.4	0.015	0.0030	0.002	0.0050	0.005	0.030	0.190	-	0.0040	Steel of the present invention
N	0.050	1.40	1.5	0.012	0.0020	0.003	0.0010	0.800	0.035	0.090	-	0.0007	Steel of the present invention
O	0.040	1.20	1.4	0.011	0.0030	0.002	0.0025	0.030	0.000	0.170	0.002	0.0012	Steel of the present invention
P	0.130	0.92	1.6	0.006	0.0035	0.004	0.0023	0.030	0.037	0.124	0.002	0.0014	Steel of the present invention
Q	0.030	1.00	1.6	0.009	0.0035	0.005	0.0017	0.037	0.020	0.140	-	0.0010	Steel of the present invention
R	0.039	0.10	1.6	0.006	0.0040	0.002	0.0029	0.450	0.030	0.120	0.002	0.0015	Steel of the present invention
S	0.030	0.50	1.6	0.009	0.0030	0.002	0.0022	0.200	0.035	0.120	-	0.0015	Steel of the present invention
T	0.030	0.70	1.2	0.008	0.0030	0.002	0.0040	0.035	0.015	0.060	0.002	0.0025	Steel of the present invention
U	0.035	0.95	1.4	0.008	0.0030	0.002	0.0035	0.035	0.030	0.130	0.002	0.0025	Steel of the present invention
V	0.040	1.00	1.5	0.070	0.0030	0.002	0.0030	0.040	0.035	0.120	0.002	0.0015	Steel of the present invention
W	0.035	1.00	0.8	0.008	0.0025	0.003	0.0040	0.034	0.015	0.080	-	0.0015	Steel of the present invention
X	0.040	1.20	0.8	0.017	0.0030	0.003	0.0020	0.080	0.030	0.100	0.002	0.0015	Steel of the present invention
Y	0.030	0.90	1.2	0.017	0.0030	0.002	0.0032	0.000	0.030	0.150	-	0.0015	Steel of the present invention
Z	0.030	0.90	1.9	0.016	0.0030	0.002	0.0035	0.033	0.025	0.110	-	0.0015	Steel of the present invention
a	0.210	1.30	1.4	0.120	0.0030	0.002	0.0031	0.005	0.015	0.080	0.002	0.0015	Steel for Comparison
b	0.040	1.00	3.6	0.020	0.0025	0.002	0.0040	0.030	0.015	0.060	-	0.0015	Steel for Comparison
c	0.030	1.00	1.5	0.020	0.0030	0.002	0.0030	0.035	0.035	0.140	0.002	0.0060	Steel for Comparison
d	0.040	0.20	1.4	0.010	0.0040	0.002	0.0029	0.030	0.030	0.150	0.002	0.0015	Steel for Comparison
e	0.040	1.10	1.4	0.010	0.0100	0.002	0.0040	0.030	0.020	0.150	0.002	0.0015	Steel for Comparison
f	0.035	0.90	1.4	0.010	0.0015	0.002	0.0003	0.030	0.025	0.120	0.002	0.0015	Steel for Comparison
g	0.035	0.90	1.4	0.010	0.0040	0.002	0.0010	0.030	0.030	0.140	0.002	0.0007	Steel for Comparison

Table 12

Steel	Right-hand side of equation 1	Right-hand side of equation 2	Right-hand side of equation 3	Left-hand side of equation 4	Middle side of equation 8	Number of precipitates/mm^2	Ar_3 °C	Remarks
A	0.0017	0.0047	0.0061	0.99	-24	3.0E+03	825	Steel of the present invention
B	0.0012	0.0045	0.0058	1.08	-19	2.8E+03	827	Steel of the present invention
C	0.0018	0.0041	0.0063	1.01	-17	3.3E+03	834	Steel of the present invention
D	0.0018	0.0068	0.0056	0.90	-45	4.3E+03	815	Steel of the present invention
E	0.0012	0.0053	0.0061	0.43	-83	3.2E+03	801	Steel of the present invention
F	0.0012	0.0053	0.0061	0.94	-29	3.2E+03	813	Steel of the present invention
G	0.0013	0.0079	0.0038	1.03	-94	4.8E+03	776	Steel of the present invention
H	0.0018	0.0061	0.0038	0.97	-98	4.6E+03	777	Steel of the present invention
I	0.0010	0.0048	0.0058	1.07	-20	3.5E+03	827	Steel of the present invention
J	0.0018	0.0061	0.0023	3.36	-9	3.7E+03	620	Steel of the present invention
K	0.0018	0.0061	0.0038	1.37	-61	4.3E+03	783	Steel of the present invention
L	0.0008	0.0134	0.0107	0.67	-6	1.2E+04	855	Steel of the present invention
M	0.0048	0.0041	0.0054	1.21	-24	4.5E+03	812	Steel of the present invention
N	0.0008	0.0041	0.0050	3.16	176	1.7E+03	815	Steel of the present invention
O	0.0014	0.0053	0.0054	1.27	-12	3.4E+03	821	Steel of the present invention
P	0.0017	0.0047	0.0047	0.99	-87	3.4E+03	754	Steel of the present invention
Q	0.0012	0.0045	0.0047	1.08	-47	3.0E+03	808	Steel of the present invention
R	0.0018	0.0053	0.0047	1.09	-48	4.2E+03	779	Steel of the present invention
S	0.0018	0.0044	0.0047	0.94	-62	3.0E+03	795	Steel of the present invention
T	0.0030	0.0052	0.0063	0.78	-41	4.3E+03	825	Steel of the present invention
U	0.0030	0.0045	0.0054	1.03	-36	3.8E+03	816	Steel of the present invention
V	0.0018	0.0054	0.0050	1.09	-40	3.8E+03	823	Steel of the present invention
W	0.0018	0.0068	0.0094	1.07	26	4.5E+03	856	Steel of the present invention
X	0.0018	0.0041	0.0094	1.38	57	2.8E+03	861	Steel of the present invention
Y	0.0018	0.0057	0.0063	0.90	-29	4.0E+03	832	Steel of the present invention
Z	0.0018	0.0061	0.0039	0.97	-87	4.3E+03	788	Steel of the present invention
a	0.0018	0.0056	0.0054	1.31	-58	3.9E+03	762	Steel for Comparison
b	0.0018	0.0068	0.0021	1.07	-242	4.5E+03	678	Steel for Comparison
c	0.0072	-0.0018	0.0050	1.08	-38	1.5E+03	817	Steel for Comparison
d	0.0018	0.0053	0.0054	0.27	-117	4.2E+03	794	Steel for Comparison
e	0.0018	0.0068	0.0054	1.17	-23	8.3E+03	818	Steel for Comparison
f	0.0018	0.0018	0.0054	0.97	-42	4.5E+02	816	Steel for Comparison
g	0.0008	0.0041	0.0054	0.97	-42	2.5E+02	816	Steel for Comparison

* Provided, however, that $Ar_3 = 896 - 509(C\%) + 26.9(Si\%) - 63.5(Mn\%) + 229(P\%)$

Table 13

Steel	Finishing Temperature	Cooling Rate	Air-cooling Start Temperature	Air-cooling Time	Coiling Temperature	Tensile Strength	Elongation	Hole-Expandability	Remarks
	°C	°C/s	°C	s	°C	N/mm²	%	%	
A1	920	70	680	4	490	801	24	112	Steel of the present invention
A2	910	70	720	2	580	846	21	101	Steel of the present invention
A3	920	40	-	-	500	818	22	120	Steel of the present invention
A4	930	10	-	-	480	808	18	80	Steel for Comparison
B1	920	70	670	5	490	820	23	110	Steel of the present invention
B2	900	70	720	2	300	795	25	107	Steel of the present invention
B3	910	70	780	3	500	837	16	102	Steel for Comparison
B4	890	40	-	-	500	849	21	110	Steel of the present invention
C1	910	70	670	3	500	811	23	111	Steel of the present invention
C2	920	40	-	-	480	813	22	121	Steel of the present invention
D1	890	70	670	4	490	863	21	104	Steel of the present invention
D2	930	70	680	3	550	893	21	94	Steel of the present invention
E1	930	70	670	3	500	738	25	121	Steel of the present invention
E2	920	40	-	-	480	740	24	128	Steel of the present invention
E3	920	70	720	3	620	810	22	50	Steel for Comparison
F1	910	70	680	3	500	771	24	116	Steel of the present invention
F2	910	40	-	-	500	783	23	124	Steel of the present invention
F3	890	70	630	4	500	783	18	100	Steel for Comparison
G1	920	70	680	3	500	806	23	112	Steel of the present invention
G2	920	70	-	-	480	808	22	121	Steel of the present invention
G3	930	40	-	-	620	878	20	60	Steel for Comparison
H1	910	70	690	3	480	772	24	116	Steel of the present invention
H2	900	40	-	-	480	784	23	124	Steel of the present invention
I1	920	70	680	3	520	834	22	108	Steel of the present invention
I2	910	40	-	-	500	836	21	118	Steel of the present invention
J1	880	70	670	4	500	990	17	88	Steel of the present invention
J2	870	10	-	-	500	1002	13	40	Steel for Comparison
K1	910	70	670	4	450	782	24	124	Steel of the present invention
K2	890	70	680	4	550	802	23	106	Steel of the present invention
L1	890	70	670	3	500	590	30	140	Steel of the present invention
L2	910	40	-	-	550	627	28	129	Steel of the present invention
M1	890	70	670	3	480	983	18	89	Steel of the present invention
M2	890	50	680	3	500	993	17	87	Steel of the present invention
N1	880	70	680	3	500	810	23	111	Steel of the present invention
N2	890	30	-	-	500	822	22	120	Steel of the present invention

Table 14 (Continued from Table 13)

Steel	Finishing Temperature	Cooling Rate	Air-cooling Start Temperature	Air-cooling Time	Coiling Temperature	Tensile Strength	Elongation	Hole-Expandability	Remarks
	°C	°C/s	°C	s	°C	N/mm²	%	%	
O1	920	70	670	5	500	830	24	103	Steel of the present invention
O2	910	70	690	3	480	820	23	110	Steel of the present invention
P1	890	70	680	3	480	873	21	106	Steel of the present invention
P2	900	70	700	4	500	883	21	103	Steel of the present invention
Q1	900	70	670	4	500	817	23	107	Steel of the present invention
Q2	890	150	660	5	480	807	24	108	Steel of the present invention
Q3	910	40	-	-	480	819	22	119	Steel of the present invention
Q4	920	40	-	-	200	769	23	60	Steel for Comparison
R1	920	70	680	3	500	738	25	118	Steel of the present invention
R2	920	40	-	-	500	750	24	128	Steel of the present invention
S1	930	100	660	5	500	787	25	111	Steel of the present invention
S2	910	70	720	2	480	777	23	124	Steel of the present invention
T1	900	70	680	3	480	608	30	138	Steel of the present invention
T2	910	40	-	-	500	630	28	140	Steel of the present invention
U1	890	70	680	4	480	809	23	111	Steel of the present invention
U2	890	40	-	-	480	821	22	118	Steel of the present invention
V1	890	70	660	3	520	818	23	110	Steel of the present invention
V2	900	70	660	4	400	798	23	122	Steel of the present invention
V3	890	40	-	-	550	845	21	117	Steel of the present invention
W1	920	70	700	3	500	820	23	110	Steel of the present invention
W2	930	70	660	3	580	860	22	99	Steel of the present invention
W3	910	40	-	-	480	822	22	122	Steel of the present invention
X1	900	70	690	3	500	812	23	112	Steel of the present invention
X2	930	70	-	-	480	802	22	119	Steel of the present invention
Y1	890	70	680	4	480	821	23	111	Steel of the present invention
Y2	910	70	690	3	400	811	22	120	Steel of the present invention
Z1	910	70	670	3	500	801	23	112	Steel of the present invention
Z2	910	70	680	3	400	791	23	126	Steel of the present invention
a1	850	70	680	3	480	795	15	60	Steel for Comparison
b1	900	70	680	4	480	859	12	105	Steel for Comparison
c1	920	70	680	3	500	850	21	50	Steel for Comparison
d1	900	70	670	4	480	782	15	115	Steel for Comparison
e1	900	70	680	3	480	749	24	70	Steel for Comparison
f1	910	70	680	4	520	788	22	78	Steel for Comparison
g1	910	70	680	3	500	812	21	75	Steel for Comparison

Table 15

Steel	Finishing Temperature	Cooling Rate	Cooling Start Temperature	Air-cooling Time	Coiling Temperature	Tensile Strength	Ratio of ds/dl ≥ 0.1	Elongation	Hole-Expandability	Remarks
	°C	°C/s	°C	s	°C	N/mm^2		%	%	
A1	920	70	680	4	490	801	91%	24	112	Steel of the present invention
A5	920	70	780	4	490	801	30%	15	112	Steel for comparison
A6	920	70	760	4	480	796	60%	16	113	Steel for comparison
A7	920	70	740	4	500	806	82%	23	112	Steel of the present invention
A8	920	80	720	4	500	806	88%	24	112	Steel of the present invention
A9	920	80	700	4	490	801	90%	24	112	Steel of the present invention
A10	920	80	660	4	490	801	92%	24	112	Steel of the present invention

Table 16

Steel	Finishing Temperature	Cooling Rate	Cooling Start Temperature	Air-cooling Time	Coiling Temperature	Tensile Strength	Ratio of Ferrite Grains Not Smaller Than 2 μm	Elongation	Hole-Expandability	Remarks
	°C	°C/s	°C	s	°C	N/mm²		%	%	
B1	920	70	670	5	490	820	85%	23	110	Steel of the present invention
B5	860	70	670	4	490	820	60%	15	110	Steel for Comparison
B6	860	70	700	4	500	825	70%	16	109	Steel for Comparison
B7	880	70	730	4	490	820	83%	23	110	Steel of the present invention
B8	920	70	730	5	500	825	90%	23	109	Steel of the present invention
B9	960	80	670	6	500	825	93%	23	109	Steel of the present invention
B10	960	80	730	6	490	820	94%	24	110	Steel of the present invention

[Industrial Applicability]

The present invention provides high-strength steel sheets having strength of the order of not lower than 590 N/mm^2, or preferably not lower than 980 N/mm^2, and an unprecedentedly good balance between ductility and hole-expandability. Therefore, the present invention is of great valve in industries using high-strength steel sheets.